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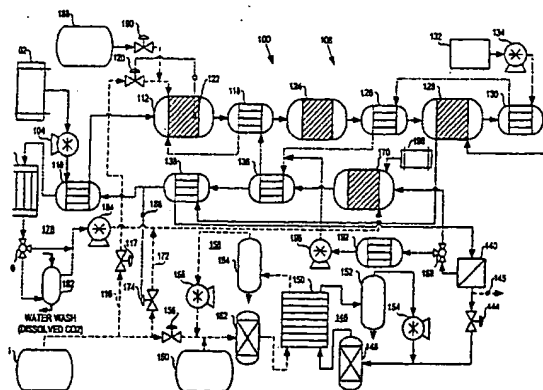
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(54) Title: FUEL CELL POWER GENERATION SYSTEM WITH AUTOTHERMAL REFORMER



(57) Abstract: A fuel cell electric power generation system comprises: (a) a fuel processing subsystem comprising an autothermal reformer (112); (b) a hydrogen separator (140) for separating the reformat stream from the fuel processing subsystem into a hydrogen-rich stream and a raffinate stream; (c) a fuel cell stack (150) comprising at least one fuel cell fluidly connected to receive an oxidant stream, and the hydrogen-rich stream from the fuel processing system; and (d) a burner (170) fluidly connected to receive the raffinate stream and to combust the raffinate stream therein to produce a burner outlet stream comprising carbon dioxide and oxygen. In one embodiment the system further comprises a carbon dioxide scrubber (182) fluidly connected to receive the burner outlet stream for removing at least a portion of the carbon dioxide from the burner outlet stream and for recovering at least a portion of the oxygen from the burner outlet stream and supplying an oxygen-containing stream to the burner. In another embodiment, the present system further comprises a turbo-compressor mechanically connected to a turbo-expander, where the turbo-compressor compresses the air to produce an oxidant stream and the turbo-expander is fluidly connected to receive the burner outlet stream from the burner. Methods of operating the present system are also provided.

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**FUEL CELL POWER GENERATION  
SYSTEM WITH AUTOTHERMAL REFORMER**

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**Field of the Invention**

The present invention relates to electrochemical fuel cell electric power generation systems. More particularly, the present invention relates to an integrated fuel cell power plant suitable for use in stationary and vehicular applications, especially for use in submarines.

**Background of the Invention**

The search for alternative power sources has focused attention on the use of electrochemical fuel cells to generate electrical power. Unlike conventional fossil fuel power sources, fuel cells are capable of generating electrical power from a fuel stream and an oxidant stream without producing substantial amounts of undesirable by-products, such as sulfur oxides, nitrogen oxides and carbon monoxide. However, the commercial viability of fuel cell electric power generation systems will benefit from the ability to efficiently and cleanly convert conventional hydrocarbon fuel sources, such as, for example, gasoline, diesel, natural gas, ethane, butane, light distillates, dimethyl ether, methanol, ethanol, propane, naphtha, kerosene, and combinations thereof, to a hydrogen-rich gas stream with increased reliability and decreased cost. The conversion of such fuel sources to a hydrogen-rich gas stream is also important for other industrial processes, as well.

Fuel cell electric power generation systems are of particular significance in the submarine industry, as they offer significant advantages relative to conventional diesel-electric and nuclear power plants often used in submarines. Fuel cell electric power generation systems offer high energy conversion efficiency and operate quietly, thereby limiting the opportunity for detection of the acoustic signature of the vessel. Air-independent submarine propulsion systems, with on-board storage of fuel and oxidant, avoid the need for snorting periods (drawing air from above the ocean surface) during a mission, reducing the optical and radar

signature of the vessel. The fuel cell propulsion system requires less on-board oxygen and fuel storage for a given mission than other air-independent propulsion systems because of the high efficiency of the fuel cell as an energy conversion device. Fuel cell powered submarines  
5 therefore offer the advantage of long submerged mission durations. Also, relative to nuclear power plants, fuel cell electric power generation systems have fewer human health and safety concerns, particularly as to fuel storage and handling.

In submarine applications, one or more fuel cell stacks may be  
10 connected in series, or, more commonly, in parallel with a conventional battery bank. Individual fuel cells and stacks are electrically connected to meet the desired voltage and current requirements of the system. The fuel cells may be used as the primary source of power for submarine propulsion and for other loads on board, and for charging the batteries. The batteries  
15 may be used to augment the fuel cell stack power output when power in excess of the maximum fuel cell output is required.

In fuel cell power generation systems, such as those used to power submarines, the fuel cell stack may be supplied with an oxidant stream composed of substantially pure oxygen or oxygen in an inert carrier gas  
20 such as nitrogen or argon, for example. The oxygen may be stored on-board the submarine as liquid oxygen ("LOX"), or may be generated on-board by decomposition of an oxygen source such as hydrogen peroxide. In some instances, the fuel cell power generation system may be adapted to use air as the oxidant stream during surface operations, thereby reserving  
25 the stored oxygen supply for operation during submersion.

The fuel stream in such systems is often substantially pure hydrogen obtained by purification of a hydrogen-containing reformat stream generated by the on-board catalytic steam reformation of a process fuel stream such as methanol, kerosene, diesel and other alcohols or  
30 hydrocarbon-based fuels. In other systems, hydrogen storage devices, such as metal hydrides or high pressure gas cylinders are used to store hydrogen fuel on-board, as well as or instead of an on-board reformer.

- 3 -

To be effectively employed in submarine applications, fuel processing components such as vaporizers, reformers and hydrogen separators should be compact, robust and reliable. Examples of radial flow fuel vaporizer and reformer designs are disclosed in U.S. Patent No. 5,676,911, which is incorporated herein by reference in its entirety.

Diffusion membrane hydrogen separators, such as palladium or palladium membrane separators, are particularly suitable for use in reformat stream purification on a submarine since they are compact and their operation is not affected by the motion of the vessel. They generally separate the reformat stream into a high-purity hydrogen stream and a raffinate stream, which is depleted in hydrogen and contains other reformat stream components, primarily carbon dioxide. The substantially pure hydrogen stream is then delivered to the fuel cell stack as the fuel stream.

A conventional palladium alloy-based hydrogen separation device includes an arrangement of thin-walled palladium alloy tubular members sealed in a shell (similar to a conventional shell-and-tube heat exchanger). Alternative approaches to metal diffusion membrane separator designs may also be used. These include composite noble metal tubes, thin film metal deposition on porous substrates, or supported rolled film designs. In these designs the metal or metal alloy film thickness is drastically reduced compared to conventional palladium alloy tubes, reducing the cost of the unit for a given capacity of gas separation. Structural strength in these designs is provided by a less expensive hydrogen permeable support material, while thin, supported metal or metal alloy film provides hydrogen selectivity. Examples of such designs are described in Edlund et al. U.S. Patent No. 5,645,626, and related patents, and in Buxbaum U.S. Patent Nos. 5,108,724 and 5,215,729.

In selecting preferred operating pressures for the fuel cells and for the reactant supply and processing systems, factors such as the need to be able to discharge waste exhaust streams overboard at diving depth should be considered. One approach is to operate the entire fuel cell power

- 4 -

generating system, including the fuel processing system and fuel cells, at a pressure higher than the typical maximum depth pressure so that waste exhaust streams may be discharged without the need for further pumping. This is the preferred option when the fuel cell is operating on a dilute or impure fuel stream, and there is not a closed fuel loop for recirculating the fuel stream through the fuel cell stack. In this case the fuel stream exiting the stack should be vented or discharged from the stack, and ultimately from the vessel, so preferably it is at high pressure.

If subsystems generating waste exhaust streams are operating at lower pressures than depth pressure, the exhaust gases should be compressed prior to discharge to the ocean, be it directly or via a scrubber. Compressing exhaust streams for discharge overboard represents a significant parasitic power load and requires the use, storage and maintenance of additional equipment. Conversely, discharging exhaust gases via a scrubber at low pressures requires significantly increases the space needed for the system, as low-pressure scrubber equipment is significantly larger than high-pressure equipment. This is also less than desirable, as space is generally at a premium on-board.

A fuel cell power generation system suitable for use in submarine applications is described in commonly assigned U.S. Patent No. 6,063,515, incorporated herein by reference in its entirety. The fuel cell power generation system described therein employs a catalytic burner to heat a heat transfer fluid, which in turn is used to heat a vaporizer and steam reformer. A hydrogen separator is used to obtain a substantially pure hydrogen fuel stream from the reformat stream, which is directed to and recirculated through the fuel cell stack in a closed loop. The fuel processing subsystem is operated at high pressure, which facilitates the discharge of waste streams overboard, and the fuel cell stack is operated at a substantially lower pressure. The preferred fuel for the fuel processing system is disclosed as a methanol-water mixture.

The use of methanol or a methanol-water mixture as a fuel for fuel processing systems for use in a submarine may be less than desirable in

some applications. Currently, methanol is not a readily available fuel, and the lack of availability may significantly limit the ports at which it may be possible to refuel. For convenience and availability diesel, such as DF-2 (No. 2 diesel), for example, would be a preferable fuel. Such fuels also  
5 have a higher energy density relative to methanol, and so would also be preferable in that a smaller volume of fuel for a given mission range would need to be stored on-board.

Diesel, however, is notoriously difficult to reform in a steam reformer. Further, the high levels of sulfur in diesel fuel typically requires  
10 sulfur removal components, such as a hydrodesulfurizer (HDS) and hydrogen sulfide scrubber, for example, to be located upstream of the steam reformer in order to avoid poisoning of the steam reformer catalyst. This adds complexity and cost to the fuel processing subsystem, and takes up additional valuable space within the vessel. Thus, employing a steam  
15 reformer to reform diesel may be less than desirable.

As mentioned above, the fuel processing subsystem of the fuel cell power generation system disclosed in U.S. Patent No. 6,063,515, operates at high pressure, thereby facilitating the discharge of waste exhaust streams overboard. The catalytic burner outlet stream is directed to a carbon  
20 dioxide dissolver, where it is dissolved in sea water at diving depth pressures and discharged overboard. The catalytic burner outlet stream may also contain a significant amount of oxygen, however, which is lost on discharge. In air-independent propulsion systems, submerged mission duration is typically limited by the amount of oxidant stored on-board.  
25 Therefore, it would be desirable to recover the oxygen lost on discharge of the waste exhaust stream.

Accordingly, it would be desirable to have a fuel cell electric power generation system for use in submarine applications, for example, that could easily and efficiently operate using diesel as a fuel, and could make  
30 more efficient use of the oxygen stored on-board when used as an air-independent propulsion system.



### Summary of the Invention

Methods and apparatus relating to the present fuel cell electric power generation system are provided.

5 In one embodiment, which is particularly suited for use in submarine applications, the present fuel cell electric power generation system comprises:

- (a) a fuel processing subsystem for converting a fuel stream to a reformat stream comprising hydrogen, the fuel processing subsystem comprising an autothermal reformer;
- 10 (b) a hydrogen separator located downstream of the fuel processing subsystem and fluidly connected thereto for receiving the reformat stream, the separator comprising a membrane for separating the reformat stream into a hydrogen-rich stream and a raffinate stream;
- 15 (c) a fuel cell stack comprising at least one fuel cell fluidly connected to receive an oxidant stream, and the hydrogen-rich stream from the hydrogen separator;
- (d) a burner fluidly connected to receive the raffinate stream and to combust the raffinate stream therein to produce a burner outlet stream comprising carbon dioxide and oxygen; and
- 20 (e) a carbon dioxide scrubber fluidly connected to receive the burner outlet stream for removing at least a portion of the carbon dioxide from the burner outlet stream and for recovering at least a portion of the oxygen from the burner outlet stream and supplying an oxygen-containing stream to
- 25 the burner.

The fuel processing subsystem of the present system may further comprise a hydrogen sulfide scrubber located downstream of the autothermal reformer and fluidly connected thereto for receiving the reformat stream. The hydrogen sulfide scrubber may comprise a metal

30 oxide absorbent bed or a hot carbonate scrubber, for example. Preferably, the hydrogen sulfide scrubber comprises a zinc oxide absorbent bed.

The fuel processing subsystem of the present system may also further comprise a shift reactor located downstream of the hydrogen sulfide scrubber and fluidly connected thereto to receive the reformat stream therefrom.

5 In the present system, the hydrogen separator may consist of plate-and-frame, spiral wound, or hollow fiber modules, for example. Preferably, the hydrogen separator can tolerate transmembrane pressure differentials of at least 2750 kPa. More preferably, the hydrogen separator can tolerate transmembrane pressure differentials of at least 3450 kPa.

10 The membrane of the hydrogen separator may comprise one or more of: palladium membranes; palladium alloy membranes; platinum membranes; platinum alloy membranes; titanium alloy membranes; ceramic membranes; zeolite molecular sieve membranes; carbon molecular sieve membranes; inorganic poly-acid membranes; and composite membranes thereof. Preferably, the membrane comprises a palladium membrane or  
15 palladium alloy membrane; more preferably, the membrane is supported.

In the present system, the fuel cell stack may comprise at least one solid polymer electrolyte fuel cell. The fuel cell stack may also comprise an array of fuel cell stacks, preferably an array of solid polymer electrolyte  
20 fuel cell stacks.

The burner of the present system may comprise a catalytic burner.

The present system may further comprise a fuel supply for supplying the fuel to the fuel processing subsystem. The fuel may consist of diesel, gasoline or liquid synthetic hydrocarbon fuels, for example.  
25 Preferably, the fuel comprises diesel fuel, such as No. 2 diesel fuel, for example.

The present system may also further comprise an oxidant supply for supplying oxidant to the fuel processing subsystem. The oxidant supply may comprise liquid oxygen, hydrogen peroxide or air, for example.

30 Where the oxidant supply comprises hydrogen peroxide, the fuel processing subsystem further comprises a decomposer for converting the hydrogen peroxide to substantially pure oxygen.

The present system may further comprise a water supply for supplying water to the fuel processing subsystem.

The present system may also further comprise a compressor fluidly connected to the carbon dioxide scrubber for pressurizing the oxygen-containing stream supplied to the burner.

Another embodiment of the present fuel cell electric power generation system comprises:

- (a) a fuel processing subsystem for converting a fuel stream to a reformat stream comprising hydrogen, the fuel processing subsystem comprising an autothermal reformer;
- (b) a hydrogen separator located downstream of the fuel processing subsystem and fluidly connected thereto for receiving the reformat stream, the separator comprising a membrane for separating the reformat stream into a hydrogen-rich stream and a raffinate stream;
- (c) a turbo-compressor mechanically connected to a turbo-expander, the turbo-compressor for compressing air to produce a compressed air stream;
- (d) a fuel cell stack comprising at least one fuel cell fluidly connected to receive the hydrogen-rich stream from the hydrogen separator, and the compressed air stream from the turbo-compressor, and producing an anode exhaust stream, a cathode exhaust stream, and electric power therefrom; and
- (e) a burner fluidly connected to receive the raffinate stream and to combust the raffinate stream therein to produce a burner outlet stream,

wherein the turbo-expander is fluidly connected to receive the burner outlet stream from the burner.

The burner may also be fluidly connected to receive the cathode exhaust stream from the fuel cell stack.

A method of operating the present fuel cell electric power generation system in a submarine comprises:

- 9 -

- 5 (a) catalytically reforming a fuel stream in an autothermal reformer to produce a reformat stream comprising hydrogen;
- (b) separating the reformat stream into a substantially pure hydrogen stream and a raffinate stream in a hydrogen separator comprising a hydrogen separation membrane;
- 10 (c) supplying the hydrogen stream and an oxidant stream from an oxidant supply to the fuel cell stack, producing an anode exhaust stream from the hydrogen stream, a cathode exhaust stream from the oxidant stream, and electrical power;
- (d) combusting the raffinate stream in a burner to produce heat and a burner outlet stream comprising carbon dioxide and oxygen;
- 15 (e) supplying the burner outlet stream to a carbon dioxide scrubber via a burner stream inlet, the scrubber comprising a water stream inlet, a water discharge stream outlet, and a gas recovery outlet, dissolving the carbon dioxide in the water stream and producing an oxygen-containing gas stream; and
- (f) supplying the oxygen-containing gas stream to the burner.
- 20 The fuel stream may comprise diesel, gasoline or liquid synthetic hydrocarbon fuels, for example. Preferably, the fuel comprises diesel fuel, more preferably No. 2 diesel fuel.

In the present method the reformat stream is preferably supplied to the hydrogen separator at a pressure in the range of about 2750 kPa to about 4150 kPa, more preferably in the range of about 3450 kPa to about 4150 kPa. The hydrogen and oxidant streams are preferably independently supplied to the stack at a pressure less than or equal to about 700 kPa, more preferably a pressure in the range of about 120 kPa to about 550 kPa.

30 The oxidant supply may comprise liquid oxygen, hydrogen peroxide or air, for example. Where the oxidant supply comprises hydrogen peroxide, the method further comprising supplying the hydrogen peroxide stream to a decomposer to convert the hydrogen peroxide stream into the

- 10 -

oxygen stream for supply to the stack. Where the oxidant supply comprises air, the method may further comprise supplying the cathode exhaust stream to the burner.

5 In the present method, the burner outlet stream is preferably supplied to the carbon dioxide scrubber at a pressure in the range of about 2750 kPa to about 4150 kPa, more preferably in the range of about 3450 kPa to about 4150 kPa.

10 The present method may further comprise regulating the pressure of the reformat stream supplied to the hydrogen separator so that the pressure is greater than the external water pressure adjacent the hull of the submarine and not less than the minimum effective operating pressure of the hydrogen separator.

Another method of operating the present fuel cell electric power generation system comprises:

- 15 (a) catalytically reforming a fuel stream in an autothermal reformer to produce a reformat stream comprising hydrogen;
- (b) separating the reformat stream in a hydrogen separator into a substantially pure hydrogen stream and a raffinate stream;
- 20 (c) compressing an air stream in a turbo-compressor to produce an oxidant stream, where the turbo-compressor is mechanically connected to a turbo-expander;
- (d) supplying the hydrogen stream and the oxidant stream to the fuel cell stack, producing an anode exhaust stream from the hydrogen stream, a cathode exhaust stream from the oxidant stream, and electrical power;
- 25 (e) combusting the raffinate stream in a burner to produce a burner outlet stream; and
- (f) supplying the burner outlet stream to the turbo-expander.
- 30

The method may further comprise supplying the cathode exhaust to the burner.

**Brief Description of the Drawing**

FIG. 1 is a schematic illustration of an embodiment of the present fuel cell electric power generation system.

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**Detailed Description of Preferred Embodiment(s)** The present fuel cell electric power generation system is capable of operating on fuels such as No. 2 diesel, for example, employing an autothermal reformer to convert the fuel to a hydrogen-rich reformat stream.

10

Autothermal reforming is an approach that combines catalytic partial oxidation and steam reforming. Partial oxidation employs substoichiometric combustion to achieve the temperatures to reform the hydrocarbon fuel. Fuel, oxidant (oxygen or air, for example), and steam are reacted to form primarily hydrogen,  $\text{CO}_2$  and  $\text{CO}$ . An advantage of autothermal reforming technology is that the exothermic combustion reactions are used to drive the endothermic reforming reaction.

15

Autothermal reformers typically employ noble metal catalyst beds operating at typical operating temperatures of from about  $870^\circ\text{C}$  to about  $1300^\circ\text{C}$ . The lower operating temperatures of steam reformers (usually at least about  $500^\circ\text{C}$  lower than the operating temperatures of autothermal reformers) generally require upstream sulfur removal from sulfur-laden fuel to avoid poisoning of the steam reforming catalyst. Common sulfur removal components of steam reforming systems include a hydrodesulfurizer (HDS) to convert the sulfur in the fuel to  $\text{H}_2\text{S}$ , and a downstream  $\text{H}_2\text{S}$  scrubber, such as a metal oxide absorbent bed. At the high operating temperatures typical of autothermal reformers, sulfur in the fuel is converted into  $\text{H}_2\text{S}$ , which does not significantly poison the catalyst and permits downstream sulfur removal. This may result in a simpler fuel processing system, as an HDS is not required. Compared to fuel processing systems employing steam reformers, start-up times also tend to be shorter due to the heat supplied to the catalyst bed by catalytic combustion.

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FIG. 1 schematically illustrates an embodiment of the present fuel cell electric power generation system. In normal operation of fuel cell power generation system 100, fuel from storage container 102 is pressurized by pump 104 and supplied to fuel processing subsystem 108 at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa. The fuel is first directed to preheater 110 where it is heated to about 300°C before introduction into autothermal reformer 112. A substantially pure oxygen stream from oxygen supply container 114 is also supplied via line 116 and valve 117 to autothermal reformer 112. Similarly, superheated steam is supplied from vaporizer 118 to autothermal reformer 112, at about 600°C. In autothermal reformer 112, the fuel, oxygen and steam are catalytically reformed into a hydrogen-rich reformat stream comprising hydrogen, carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), and water vapor, and that may further comprise H<sub>2</sub>S, some unreacted fuel and trace C<sub>2</sub>-C<sub>6</sub> fuel combustion/cracking by-products.

Autothermal reformer 112 is typically operated at temperatures in the range of about 850°C to about 1050°C, preferably about 970°C, to ensure substantially complete conversion of methane and heavy and intermediate hydrocarbon products (such as C<sub>2</sub> and C<sub>6</sub> hydrocarbons, for example) in the reformat stream. To increase system efficiency, autothermal reformer 112 is preferably operated at a steam-to-carbon ratio in the range of about 2 to about 3, more preferably about 2.5.

The reformat stream exits autothermal reformer 112 at temperatures in the range from about 870°C to about 1300°C, preferably from about 900°C to about 1000°C. The operating temperature of reformer 112 is maintained within the desired range by controlling the amount of oxygen supplied to reformer 112 so that the oxygen-to-carbon ratio is in a range of about 0.3 to about 0.5, more preferably about 0.4. Valve 120 controls and maintains the amount of oxygen supplied to reformer 112 from oxygen supply container 114 in response to the catalyst

bed temperature of reformer 112, which is measured by temperature sensor 122 disposed therein.

The reformat stream is then directed to vaporizer 118 where it heats a water/steam mixture flowing therethrough by heat exchange.

5 Alternatively, vaporizer 118 and autothermal reformer 112 may be integrated in a single vessel, if desired.

The reformat stream exits vaporizer 118 and is supplied to H<sub>2</sub>S scrubber 124. H<sub>2</sub>S scrubber 124 removes at least a portion of the H<sub>2</sub>S from the reformat stream. Preferably, the size of H<sub>2</sub>S scrubber 124 is  
10 suitably chosen so as to remove substantially all of the H<sub>2</sub>S from the reformat stream.

H<sub>2</sub>S scrubber 124 may comprise any suitable component for removing H<sub>2</sub>S from a gas stream. For example, an absorbent bed comprising a metal oxide may be used. In this regard, absorbent beds  
15 comprising, for example, iron, zinc, nickel, copper, manganese, or molybdenum oxides, or mixtures and/or mixed oxides of the foregoing, may be employed. Examples of such metal oxide absorbent beds are described in U.S. Patent Nos. 5,244,641, 5,277,351, 5,769,909, and 5,792,438. As another example, hot carbonate H<sub>2</sub>S scrubbers, such as  
20 described in U.S. Patent No. 4,297,330, may also be employed. ZnO absorbent beds are preferred.

The reformat stream then exits H<sub>2</sub>S scrubber 124 and is directed to shift precoolers 126 where the reformat stream is cooled by heat exchange with water flowing through shift precoolers 126 to a temperature within the  
25 operating temperature range of shift reactor 128.

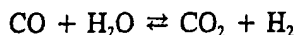
The reformat stream exiting shift precoolers 126 is supplied to the inlet of shift reactor 128, which comprises a shift catalyst bed and heat exchange elements associated therewith that are fluidly isolated from the catalyst bed. Preferably, shift reactor 128 is sized so that the shift catalyst  
30 bed is provided with an upstream sacrificial adiabatic bed for absorbing any remaining H<sub>2</sub>S in the reformat stream not removed by H<sub>2</sub>S scrubber 124.



- 14 -

More preferably, the sacrificial adiabatic bed is designed for easy removal and replacement during maintenance.

In shift reactor 128, carbon monoxide is combined with water in the catalyst bed to yield carbon dioxide and hydrogen according to the water gas shift reaction:



The reaction is exothermic, requiring some sort of temperature control to maintain the shift catalyst bed within a suitable operating temperature range. In the present embodiment, the reformat exiting shift reactor 128 is supplied to shift intercooler 130 where the reformat stream is cooled by heat exchange with water flowing through shift intercooler 130. The cooled reformat stream is then redirected to the heat exchange elements of shift reactor 128 in order to moderate the temperature of the catalyst bed by heat exchange. Alternatively, water or another suitable heat exchange fluid could be directed through heat exchange elements of shift reactor 128 directly, in which case shift intercooler 130 could be eliminated. Such heat exchange elements could be external and separate from shift reactor 128, or may be integrated in the reactor vessel, if desired.

Water is the preferred primary heat exchange fluid for fuel processing subsystem 108. Water from water supply 132 is pressurized by pump 134 and supplied to shift intercooler 130, where it is circulated and heated by heat exchange with the reformat stream in shift intercooler 130. The water stream exits shift intercooler 130 and is supplied to shift precooler 126 where the water is further heated by heat exchange with the reformat stream. The water stream is then supplied to prevaporizer 136 and is at least partially converted into steam therein to produce a water/steam mixture. The water/steam mixture is then supplied to vaporizer 118, where it is converted to steam and superheated before introduction into autothermal reformer 112, as described.

Other heat transfer fluids may also be employed as the heat exchange fluid in fuel cell electric power generation system 100, such as thermal oils, for example. Where a heat transfer fluid other than water is employed, however, water will still need to be supplied to prevaporizer 136 and vaporizer 118, of course. In addition, while the present fuel cell electric power generation system is illustrated with the fuel processing subsystem having heat exchange elements arranged in staggered series, other heat exchange fluid flowpath configurations may also be employed, as desired.

10           The reformat stream exiting shift reactor 128 is then supplied to hydrogen separator preheater 138, where it is heated to a desired temperature preferably within a suitable operating temperature range of hydrogen separator 140. The heated reformat stream exits preheater 138 and is supplied to hydrogen separator 140, where the reformat stream is  
15           separated into a substantially pure hydrogen fuel stream and a raffinate stream. Hydrogen separator 140 comprises at least one hydrogen separation membrane. In operation the reformat stream entering hydrogen separator 140 is at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa. The raffinate  
20           stream is also at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa, whereas the hydrogen stream exiting hydrogen separator 140 is at a pressure less than about 700 kPa, and preferably in the range of about 120 kPa to about 550 kPa.

25           The hydrogen separation membrane(s) of hydrogen separator 140 may comprise: a metal membrane (for example, palladium, palladium alloy, or titanium alloy membrane); a polymeric material (for example, porous or microporous polyaramides, polyimides, polyketones, polysulfones, siloxane- and silane-based polymers, and cellulose acetate-  
30           based polymers); ceramic membranes (for example, porous silica membranes, porous or dense metal oxide membranes); zeolite molecular sieves; carbon molecular sieves; and inorganic poly-acids (for example,

poly-antimonic acids and polyphosphates); and composite membranes thereof. The membranes may be supported or unsupported. They may be flat films or films of various other shapes, such as cylinders, for example. The membranes may comprise modules such as, for example, plate-and-frame, spiral wound, or hollow fiber modules. Supported thin film metal diffusion membranes of palladium or palladium alloy are preferred.

The substantially pure hydrogen stream exiting hydrogen separator 140 is supplied as a fuel stream to line 142, which is controlled by valve 144, and directed to fuel loop 146. Pressure regulating valve 144 controls the amount of hydrogen supplied to fuel loop 146 from hydrogen separator 140 in response to the pressure within fuel loop 146 downstream of valve 144. The amount of reactants supplied to autothermal reformer 112 is also controlled in response to the amount of hydrogen in the fuel stream, as measured by hydrogen pressure sensor 145.

The fuel stream is first directed to humidifier 148 and humidified therein. The humidified fuel is then supplied to fuel cell stack 150 at a pressure less than about 700 kPa, and preferably in the range of about 120 kPa to about 550 kPa, where it is circulated through the anodes of the fuel cells comprising stack 150 (not shown).

Fuel cell stack 150 comprises a plurality of fuel cells electrically connected in series, in parallel, or in a combination thereof, to provide a desired overall voltage and power output of the system. Fuel cell stack 150 may be an array comprising a plurality of fuel cell stacks. Any suitable fuel cells may be employed, such as alkaline, phosphoric acid, or solid polymer electrolyte fuel cells, for example. Solid polymer electrolyte fuel cell stacks are preferred. Fuel cell stack 150 produces DC power; fuel cell electric power generation system 100 may further comprise a power conversion device (not shown). For example, system 100 may further comprise a DC-DC power converter for converting unregulated DC power to regulated DC power. As another example, system 100 may further comprise a power inverter for converting the DC power output of stack 150 to AC power, if desired.

The anode exhaust stream exiting stack 150 enters knock-out drum 152 to condense and collect liquid water from the exhaust stream. The exhaust stream is then pressurized in pump 154 before being supplied to line 142 for recirculation through stack 150. Because the fuel stream is substantially pure hydrogen, it may be recirculated through the stack via fuel loop 146 for prolonged operating periods without significant accumulation of inerts or impurities in the loop. However, a purge valve may be incorporated into fuel loop 146, if desired, to provide the facility to occasionally purge or bleed fuel loop 146, such as during surface operations, for example.

A substantially pure oxygen stream is supplied from oxygen supply container 114 via valve 156 to oxidant loop 158. To control the voltage output of fuel cell stack 150, the concentration of oxygen within oxidant loop 158 may be varied in response to the demands of the electrical load on the system. Preferably, an inert gas stream from inert gas supply 160 is mixed with the substantially pure oxygen stream to produce an oxidant stream comprising 20% to 100% oxygen, preferably 20% to 60% oxygen. "Inert gas" means a gas stream comprising a gas that is substantially unreactive in the fuel cell stack, the fuel processing system, or both: suitable inert gases include nitrogen, argon, helium, or carbon dioxide, or any combination thereof, for example (carbon dioxide is considered an inert gas in the fuel cell stack if supplied thereto to the exclusion of hydrogen). Nitrogen and argon are preferred inert gases for use in oxidant loop 158. Oxidant loop 158 may be precharged with inert gas to half the full power design pressure, to ensure that the oxygen concentration at full power is only about 50%. A fixed quantity of inert gas may thus be recirculated, with varying partial pressures of oxygen.

The oxidant stream in oxidant loop 158 is directed to humidifier 162 and humidified therein. The humidified oxidant stream is then directed to fuel cell stack 150 at a pressure less than about 700 kPa, and preferably in the range of about 120 kPa to about 550 kPa, where it is circulated through the cathodes thereof (not shown). The cathode exhaust stream exiting stack

150 enters knock-out drum 164 to condense and collect liquid water from the exhaust stream. The cathode exhaust stream is then pressurized in pump 166 before being mixed with the oxidant stream and supplied to humidifier 162 for recirculation through stack 150. Oxidant loop 158 may  
5 also further comprise a purge valve, if desired, to provide the facility to occasionally purge or bleed oxidant loop 158, such as during surface operations, for example.

The raffinate stream exiting hydrogen separator 140, which comprises hydrogen, CO<sub>2</sub>, water vapor, and a small amount of unreacted  
10 methane, and may further comprise trace CO and/or C<sub>2</sub>-C<sub>6</sub> fuel combustion/cracking by-products, is directed to via valve 168 to catalytic burner 170 at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa. The raffinate stream is mixed with an oxidant stream and combusted within the catalyst bed of  
15 burner 170 (not shown). A substantially pure oxygen stream is supplied to burner 170 from oxygen supply container 114 via line 172, which is controlled by valve 174. Oxygen is also supplied to burner 170 via oxygen recovery loop 178 (discussed below). The combustion gases exit burner 170 as a burner outlet stream.

20 The burner outlet stream exiting burner 170 is supplied to prevaporizer 136 where it is cooled by heat exchange with the water/steam mixture circulating therein. The burner outlet stream is then supplied to hydrogen separator preheater 138 and preheater 110, respectively, and further cooled by heat exchange, before being supplied to oxygen recovery  
25 loop 178.

Oxygen recovery loop 178 comprises condenser 180, CO<sub>2</sub> scrubber 182, and recycle blower 184. The cooled burner outlet stream enters condenser 180 where liquid water from the gas stream is condensed and collected. The burner outlet stream exiting from condenser 180 is then  
30 directed to CO<sub>2</sub> scrubber 182 at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa. The pressure of the burner outlet stream allows the CO<sub>2</sub> contained therein

to be readily dissolved in a seawater stream directed through CO<sub>2</sub> scrubber 182 by a pump (not shown) at diving depths and discharged from the vessel without increasing the pressure of the burner outlet stream through a ramping-up process. A significant parasitic load associated with conventional submarine electric power generation systems is thereby eliminated. Further, low-pressure CO<sub>2</sub> scrubbers are significantly larger than high-pressure CO<sub>2</sub> scrubbers. The pressure of the burner outlet stream, by allowing use of a high-pressure CO<sub>2</sub> scrubber, may also decrease the size of the overall system, as well.

The burner outlet stream also typically comprises about 3-4% oxygen, which does not dissolve in the seawater within CO<sub>2</sub> scrubber 182 to any appreciable extent. Instead, the oxygen is collected and supplied to recycle blower 184, where it is pressurized and supplied to catalytic burner 170 at a pressure from about 2750 kPa to about 4150 kPa, or more preferably from about 3450 kPa to about 4150 kPa. Valve 174 controls and maintains the amount of oxygen supplied to burner 170 from oxygen supply container 114 in response to the concentration of oxygen in the burner outlet stream, which is measured by oxygen sensor 186. As oxygen is consumed in burner 170, valve 174 provides additional oxygen to maintain the oxygen concentration in the burner exhaust stream at a level within a predetermined range. Thus, oxygen recovery loop 178 allows for efficient discharge of exhaust CO<sub>2</sub> while recovering oxygen in the burner outlet stream that may be lost in conventional submarine electric power generation systems. In air-independent propulsion applications, this may provide for a longer submerged mission duration, as the oxygen supply source tends to be the limiting factor in air-independent propulsion systems.

On start-up of the present fuel cell electric power generation system, an inert gas, preferably CO<sub>2</sub>, is heated and cycled through the fuel processing components in order to pre-heat them. For example, in fuel cell electric generation system 100 of FIG. 1, pressurized CO<sub>2</sub> from CO<sub>2</sub> supply 188 is supplied via valve 190 to charge fuel processing subsystem 108 with a predetermined volume of CO<sub>2</sub>. Once fuel processing subsystem is

- 20 -

charged, valve 190 closes. The CO<sub>2</sub> will be circulated through fuel processing subsystem for heating. The CO<sub>2</sub> flows through fuel processing subsystem 108, through hydrogen separator preheater 138, and into hydrogen separator 140. The CO<sub>2</sub> stream exits hydrogen separator 140 and is supplied via 3-way valve 168 to recycle cooler 192. Recycle cooler 192 assists in maintaining the temperature of the inert gas stream within a desired range by cooling it, as desired, in heat exchange with water flowing through recycle cooler 192 (water source and circulation not shown). The CO<sub>2</sub> stream exits recycle cooler 192 and is directed to recycle compressor 196. The CO<sub>2</sub> stream then exits recycle compressor 196 and is directed to prevaporizer 136 and from there to vaporizer 118 and autothermal reformer 112 to complete the start-up inert gas loop. During start-up fuel and oxygen are not supplied to fuel processing subsystem 108, nor is heat exchange fluid circulated therethrough.

Fuel from start fuel supply 198 is then supplied to burner 170. (While start fuel supply 198 is illustrated as separate from fuel supply 102, it is to be understood that start fuel supply 198 and fuel supply 102 may represent the same fuel source or independent sources of fuel.) Preferably, start fuel supply 198 and fuel supply 102 are the same. A substantially pure oxygen stream is also supplied from oxygen supply container 114 via line 172 to burner 170, as well as recycled burner exhaust stream from oxygen recovery loop 178, as previously described. The fuel and oxidant stream are mixed and combusted within burner 170; combustion may be initiated catalytically or if cold burner 170 may further comprise a pilot burner, ignitor, or similar such mechanism for initiating combustion. The combustion gases exit burner 170 as a burner outlet stream and are directed to prevaporizer 136 where the burner outlet stream heats the CO<sub>2</sub> stream in the inert gas loop by heat exchange. The burner outlet stream is also directed through hydrogen separator preheater 138, fuel preheater 110, and condenser 180, as described previously. The burner outlet stream is then diverted by valve 200 to recycle blower 184 (bypassing CO<sub>2</sub> scrubber 182) and supplied to burner 170. The recycle rate of the burner outlet stream is

preferably controlled so as to moderate the flame temperature of burner 170 and thus moderate the rate of heating of the components of fuel processing subsystem 108 during start-up.

5 Heating of the components of fuel processing subsystem 108 by the recycled inert gas continues until at least a portion of them reach desired initial operating temperatures, which may be less than the corresponding minimum normal operating temperature for the component. Once this state is reached, valve 168 directs the flow of the heated inert gas directly to burner 170 and recycle blower 196 is shut off, stopping the flow of CO<sub>2</sub> in  
10 the start-up inert gas loop. This is the "hot standby" state of fuel cell electric generation system 100. Once a hot standby state has been achieved, it may be maintained as desired by starting recycle blower 196 and initiating flow of CO<sub>2</sub> in the start-up inert gas loop.

The start-up process continues by supplying fuel, oxygen, and steam  
15 to autothermal reformer 112, as described previously. Ignition of the fuel-oxidant-steam mixture within autothermal reformer 112 may be achieved catalytically or autothermal reformer 112 may further comprise a pilot burner, ignitor, or similar such mechanism for initiating combustion. Autothermal reformer 112 pressurizes and is heated to normal operating  
20 temperature. Once autothermal reformer 112 reaches normal operating temperature, valve 200 is adjusted to permit flow of the burner outlet stream to CO<sub>2</sub> scrubber 182, and normal operation of fuel cell electric power generation system 100 is initiated.

Alternatively, conventional means for heating the present fuel cell  
25 electric power generation system during start-up could be used, such as electric heating elements disposed within the fuel processing components. Such conventional methods may be less desirable in certain applications, since electric heating elements tend to heat the fuel processing components unevenly, which may result in mechanical stresses placed on the  
30 components, and they are a drain on battery power. The described start-up sequence used to heat the fuel processing components of the present fuel cell electric power generation system is preferred as it tends to heat up the



- 22 -

fuel processing components more evenly, reducing stress on equipment, and minimizes use of battery power.

5 A typical shutdown sequence for fuel cell electric power generation system 100 involves purging the system with an inert gas and cooling of fuel processing subsystem 108. For example, shutdown may be initiated by interrupting supply of oxygen and fuel to fuel processing subsystem 108 by closing valve 117 stopping pump 104, respectively. Steam is preferably supplied to autothermal reformer 112 at a suitably low purge flow rate. Inert gas is then supplied to fuel processing subsystem from CO<sub>2</sub> supply 10 188, as described previously. The pressure in autothermal reformer 112, and fuel processing subsystem 108, drops as remaining hydrogen and CO<sub>2</sub> therein are consumed. After substantially all of the hydrogen within fuel processing subsystem 108 is consumed, supply of steam to autothermal reformer 112 is interrupted and the remaining steam in fuel processing 15 subsystem 108 is purged with CO<sub>2</sub>. Once the fuel processing subsystem is substantially flushed with inert gas, CO<sub>2</sub> flow is interrupted and fuel processing subsystem 108 is allowed to cool, completing the shutdown process.

20 While the present fuel cell electric power generation system is described employing No. 2 diesel as fuel, other fuels are also suitable, such as gasoline or other grades of diesel. For example, low-sulfur diesel could be employed. The use of low-sulfur diesel, for example, may result in a reduced maintenance cycle for the fuel processing subsystem, in particular the ZnO bed or other H<sub>2</sub>S scrubbing components, and/or may permit the 25 use of smaller H<sub>2</sub>S scrubbing components. As another example, zero-sulfur liquid synthetic hydrocarbon fuels could also be employed. The main advantage of employing such fuels may include elimination of H<sub>2</sub>S scrubbing components from the fuel processing subsystem, ease of reforming, and reduction in the maintenance cycle and/or size of the shift 30 reactor. The main disadvantage with using such alternate fuels is primarily their lack of ready availability.

In the present fuel cell electric power generation system, the oxygen supply may comprise liquid oxygen, air, or another oxygen source such as hydrogen peroxide, for example. Where the oxygen supply comprises air, an inert gas source may not be required in the oxidant supply loop. Where  
5 the oxygen source comprises hydrogen peroxide, the system will further comprise a decomposer for converting the hydrogen peroxide to an oxygen stream.

As stated above, the preferred operating pressure for fuel processing subsystem 108 is from about 2750 kPa to about 4150 kPa, or more  
10 preferably from about 3450 kPa to about 4150 kPa. In submarine applications, the operating pressure of fuel processing subsystem 108 may be controlled by a pressure regulator that is responsive to depth pressure. The regulator may be set, for example, to maintain the pressure in a preferred high pressure range, (such as 2750 kPa to 4150 kPa) even at  
15 substantially lower depth pressures, or at least at a minimum pressure which is preferred for operation of hydrogen separator 140. The regulator may however be adjusted, for example, to maintain the operating pressure of fuel processing subsystem 108 at a variable pressure which is a fixed amount higher than depth pressure, thus the fuel processing subsystem 108  
20 may be operated at lower pressures than 2750 kPa at shallower depths. In other applications, the operating pressure of fuel processing subsystem 108 may be set at any minimum pressure which is preferred for operation of the hydrogen separator 140.

The system illustrated in FIG. 1 may be modified for submarine  
25 applications to allow it to operate on atmospheric air during surface operations, in addition to the oxygen supply which is used as the oxygen source when the submarine is submerged. This conserves the oxygen supplies, and can reduce or eliminate the need to maintain on-board diesel generators and/or battery banks, thereby reducing the size and complexity  
30 of the submarine power plant. The atmospheric air could, for example, be compressed using a turbo-compressor mechanically connected to a turbo-expander, which in turn would receive energy from the burner outlet

- 24 -

stream. In this mode of operation, compressed atmospheric air would be directed to the fuel cell stack. The oxygen-depleted oxidant exhaust stream from the fuel cell stack would be directed to the catalytic burner inlet (not recirculated through the stack), and the burner outlet stream would be discharged to the atmosphere via the turbo-expander. In this manner, the present fuel cell electric power generation system may also be employed in stationary electric power generation applications, and in other vehicular applications, such as surface ships, trains, and industrial and heavy-duty vehicles, for example, where air-independent propulsion systems are not required and there is no corresponding requirement for on-board oxygen storage.

While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings. It is therefore contemplated that the appended claims cover such modifications as incorporate those features that come within the scope of the invention.

20

**What is claimed is:**

1. A fuel cell electric power generation system comprising:

(a) a fuel processing subsystem for converting a fuel stream to a reformat stream comprising hydrogen, said fuel processing subsystem comprising an autothermal reformer;

(b) a hydrogen separator located downstream of said fuel processing subsystem and fluidly connected thereto for receiving said reformat stream, said separator comprising a membrane for separating said reformat stream into a hydrogen-rich stream and a raffinate stream;

(c) a fuel cell stack comprising at least one fuel cell fluidly connected to receive an oxidant stream, and said hydrogen-rich stream from said hydrogen separator;

(d) a burner fluidly connected to receive said raffinate stream and to combust said raffinate stream therein to produce a burner outlet stream comprising carbon dioxide and oxygen; and

(e) a carbon dioxide scrubber fluidly connected to receive said burner outlet stream for removing at least a portion of the carbon dioxide from said burner outlet stream and for recovering at least a portion of the oxygen from said burner outlet stream and supplying an oxygen-containing stream to said burner.

2. The system of claim 1 wherein said fuel processing

subsystem further comprises a hydrogen sulfide scrubber located downstream of said autothermal reformer and fluidly connected thereto for receiving said reformat stream.

3. The system of claim 2 wherein said hydrogen sulfide

scrubber is selected from the group consisting of metal oxide absorbent beds and hot carbonate scrubbers.

4. The system of claim 2 wherein said hydrogen sulfide scrubber comprises a zinc oxide absorbent bed.

5. The system of claim 2 wherein said fuel processing subsystem further comprises a shift reactor located downstream of said hydrogen sulfide scrubber and fluidly connected thereto to receive said reformat stream therefrom.

6. The system of claim 1 wherein said reformat stream further comprises hydrogen sulfide, said fuel processing subsystem further comprising a hydrogen sulfide remover for removing at least a portion of said hydrogen sulfide from said reformat stream.

7. The system of claim 6 wherein said fuel processing subsystem further comprises a shift reactor located downstream of said hydrogen sulfide remover and fluidly connected thereto to receive said reformat stream therefrom.

8. The system of claim 1 wherein said membrane is selected from the group consisting of palladium membranes, palladium alloy membranes, platinum membranes, platinum alloy membranes, titanium alloy membranes, ceramic membranes, zeolite molecular sieve membranes, carbon molecular sieve membranes, inorganic poly-acid membranes, and composite membranes thereof.

9. The system of claim 8 wherein said membrane comprises a membrane selected from the group consisting of a palladium membrane and a palladium alloy membrane.

10. The system of claim 9 wherein said membrane is supported.

11. The system of claim 1 wherein said hydrogen separator is selected from the group consisting of plate-and-frame, spiral wound, and hollow fiber modules.

5                   12. The system of claim 1 wherein said hydrogen separator can tolerate transmembrane pressure differentials of at least 2750 kPa.

13. The system of claim 1 wherein said hydrogen separator can tolerate transmembrane pressure differentials of at least 3450 kPa.

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14. The system of claim 1 wherein said fuel cell stack comprises at least one solid polymer electrolyte fuel cell.

15                   15. The system of claim 14 wherein said fuel cell stack comprises an array of fuel cell stacks.

16. The system of claim 1 wherein said burner is a catalytic burner.

20                   17. The system of claim 1, further comprising a fuel supply for supplying said fuel to said fuel processing subsystem.

18. The system of claim 17 wherein said fuel is selected from the group consisting of diesel, gasoline and liquid synthetic hydrocarbon fuels.

25

19. The system of claim 17 wherein said fuel comprises diesel fuel.

30                   20. The system of claim 19 wherein said fuel comprises No. 2 diesel fuel.

21. The system of claim 1, further comprising an oxidant supply for supplying oxidant to said fuel processing subsystem.

5 22. The system of claim 21 wherein said oxidant supply comprises liquid oxygen.

23. The system of claim 21 wherein said oxidant supply comprises hydrogen peroxide, and said fuel processing subsystem further comprises a decomposer for converting the hydrogen peroxide to  
10 substantially pure oxygen.

24. The system of claim 21 wherein said oxidant supply comprises air.

15 25. The system of claim 1, further comprising a water supply for supplying water to said fuel processing subsystem.

26. The system of claim 1, further comprising a compressor fluidly connected to said carbon dioxide scrubber for pressurizing said  
20 oxygen-containing stream supplied to said burner.

27. A fuel cell electric power generation system for a submarine comprising the system of claim 1.

25 28. A fuel cell electric power generation system comprising:  
(a) a fuel processing subsystem for converting a fuel stream to a reformat stream comprising hydrogen, said fuel processing subsystem comprising an autothermal reformer;  
(b) a hydrogen separator located downstream of said fuel  
30 processing subsystem and fluidly connected thereto for receiving said reformat stream, said separator comprising a

- 29 -

membrane for separating said reformat stream into a hydrogen-rich stream and a raffinate stream;

(c) a turbo-compressor mechanically connected to a turbo-expander, said turbo-compressor for compressing air to produce a compressed air stream;

(d) a fuel cell stack comprising at least one fuel cell fluidly connected to receive said hydrogen-rich stream from said hydrogen separator, and said compressed air stream from said turbo-compressor, and producing an anode exhaust stream, a cathode exhaust stream, and electric power therefrom; and

(e) a burner fluidly connected to receive said raffinate stream and to combust said raffinate stream therein to produce a burner outlet stream,

wherein said turbo-expander is fluidly connected to receive said burner outlet stream from said burner.

29. The system of claim 28 wherein said burner is fluidly connected to receive said cathode exhaust stream from said fuel cell stack.

30. The system of claim 28 wherein said fuel cell stack comprises at least one solid polymer electrolyte fuel cell.

31. The system of claim 30 wherein said stack comprises an array of fuel cell stacks.

32. A method of operating a fuel cell electric power generation system for a submarine, said system comprising a fuel cell stack, said method comprising:

(a) catalytically reforming a fuel stream in an autothermal reformer to produce a reformat stream comprising hydrogen;



- 30 -

- (b) separating said reformat stream into a substantially pure hydrogen stream and a raffinate stream in a hydrogen separator comprising a hydrogen separation membrane;
- (c) supplying said hydrogen stream and an oxidant stream from an oxidant supply to said fuel cell stack, producing an anode exhaust stream from said hydrogen stream, a cathode exhaust stream from said oxidant stream, and electrical power;
- (d) combusting said raffinate stream in a burner to produce heat and a burner outlet stream comprising carbon dioxide and oxygen;
- (e) supplying said burner outlet stream to a carbon dioxide scrubber via a burner stream inlet, said scrubber comprising a water stream inlet, a water discharge stream outlet, and a gas recovery outlet, dissolving said carbon dioxide in said water stream and producing an oxygen-containing gas stream; and
- (f) supplying said oxygen-containing gas stream to said burner.

33. The method of claim 32 wherein said fuel stream comprises a fuel selected from the group consisting of diesel, gasoline and liquid synthetic hydrocarbon fuels.

34. The method of claim 32 wherein said fuel stream comprises diesel fuel.

35. The method of claim 34 wherein said fuel stream comprises No. 2 diesel fuel.

36. The method of claim 32 wherein said reformat stream is supplied to said hydrogen separator at a pressure in the range of about 2750 kPa to about 4150 kPa.

5                   37. The method of claim 32 wherein said reformat stream is supplied to said hydrogen separator at a pressure in the range of about 3450 kPa to about 4150 kPa.

10                   38. The method of claim 32 wherein said stack comprises at least one solid polymer electrolyte fuel cell.

39. The method of claim 38 wherein said stack is an array of fuel cell stacks.

15                   40. The method of claim 32 wherein said hydrogen stream is supplied to said stack at a pressure less than or equal to about 700 kPa.

20                   41. The method of claim 32 wherein said hydrogen stream is supplied to said stack at a pressure in the range of about 120 kPa to about 550 kPa.

42. The method of claim 32 wherein said oxidant stream is supplied to said stack at a pressure less than or equal to about 700 kPa.

25                   43. The method of claim 32 wherein said oxidant stream is supplied to said stack at a pressure in the range of about 120 kPa to about 550 kPa.

30                   44. The method of claim 32 wherein said oxidant supply comprises liquid oxygen.

45. The method of claim 32 wherein said oxidant supply comprises hydrogen peroxide and said oxidant stream comprises an oxygen stream, said method further comprising supplying said hydrogen peroxide stream to a decomposer to convert said hydrogen peroxide stream into said oxygen stream for supply to said stack.

46. The method of claim 32 wherein said oxidant supply comprises air.

47. The method of claim 32 wherein said cathode exhaust stream is supplied to said burner.

48. The method of claim 32 wherein said burner is a catalytic burner.

49. The method of claim 32 wherein said burner outlet stream is supplied to said carbon dioxide scrubber at a pressure in the range of about 2750 kPa to about 4150 kPa.

50. The method of claim 32 wherein said burner outlet stream is supplied to said carbon dioxide scrubber at a pressure in the range of about 3450 kPa to about 4150 kPa.

51. The method of claim 32, further comprising regulating the pressure of said reformat stream supplied to said hydrogen separator so that said pressure is greater than the external water pressure adjacent the hull of said submarine and not less than the minimum effective operating pressure of said hydrogen separator.

52. A method of operating a fuel cell electric power generation system comprising a fuel cell stack, said method comprising:

- 33 -

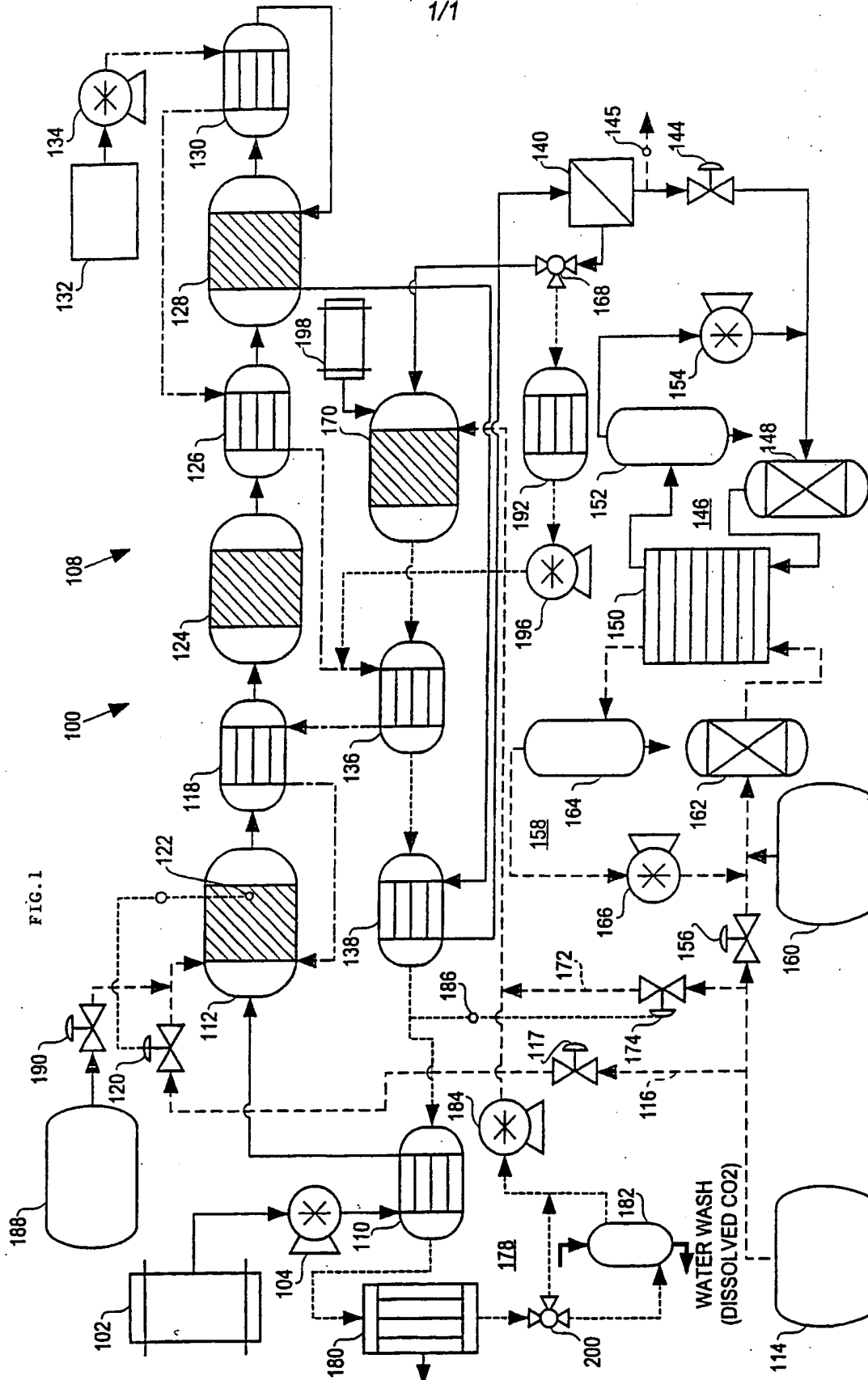
- (a) catalytically reforming a fuel stream in an autothermal reformer to produce a reformat stream comprising hydrogen;
- 5 (b) separating said reformat stream in a hydrogen separator into a substantially pure hydrogen stream and a raffinate stream;
- (c) compressing an air stream in a turbo-compressor to produce an oxidant stream, said turbo-compressor mechanically connected to a turbo-expander;
- 10 (d) supplying said hydrogen stream and said oxidant stream to said fuel cell stack, producing an anode exhaust stream from said hydrogen stream, a cathode exhaust stream from said oxidant stream, and electrical power;
- 15 (e) combusting said raffinate stream in a burner to produce a burner outlet stream; and
- (f) supplying said burner outlet stream to said turbo-expander.

20 53. The method of claim 52, further comprising supplying said cathode exhaust to said burner.

54. The method of claim 52 wherein said fuel cell stack comprises at least one solid polymer electrolyte fuel cell.

25 55. The method of claim 54 wherein said stack is an array of fuel cell stacks.

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## INTERNATIONAL SEARCH REPORT

International Application No  
PCT/CA 00/01145

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 C01B3/38 C01B3/48 H01M8/06

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 C01B H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, INSPEC, COMPENDEX, EPO-Internal, API Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	page 10, line 13 -page 15, line 6 IDEM	28-31, 52-55
X	WO 94 02409 A (CDSS LTD ;FOX THOMAS HARVEY (GB)) 3 February 1994 (1994-02-03)	1,8-10, 16,18, 21-23, 32,33, 45,48
Y	page 4, paragraph 2 -page 6, paragraph 3 figure IDEM	28-31, 52-55
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

## \* Special categories of cited documents:

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\*P\* document published prior to the international filing date but later than the priority date claimed

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\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*Z\* document member of the same patent family

Date of the actual completion of the international search

1 February 2001

Date of mailing of the international search report

09/02/2001

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# INTERNATIONAL SEARCH REPORT

Inte. onal Application No  
PCT/CA 00/01145

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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